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ALTERNATE PRODUCTION PROCESSES FOR FUZE PINIONS

National Materials Advisory Board (NAS-NRC)

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Army Materiel Command

January 1974

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A study was conducted of possible methods for producing small pinions that would not involve use of imported machinery or scarce skills. Four methods were identified: zinc die casting, plastic molding, powder compaction, and chemical etching/diffusion bonding. All processes are probably economically competitive, but each has some limitations, which are outlined. Additional recommendations of a more general nature are included.

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ALTERNATE PRODUCTION PROCESSES
FOR FUZE PINIONS

REPORT OF THE

AD HOC COMMITTEE ON ARTILLERY
FUZE PINION GEARS

NATIONAL MATERIALS ADVISORY BOARD
DIVISION OF ENGINEERING - NATIONAL RESEARCH COUNCIL

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The contribution of Mr. E. R. Cunningham of Cyclops Corporation, especially to Committee discussion of cold formability, is acknowledged with thanks.

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INTRODUCTION

A. OVERVIEW OF THE PROBLEM

As presented to the Committee, the fabrication of fuze pinions is dependent upon foreign manufacturing capability involving either domestic manufacture of pinions with foreign-made equipment or importation of pinions from foreign suppliers. For obvious reasons, the government is desirous of shifting this dependency to a totally domestically based capacity. This particular problem has resulted primarily because the United States has never really developed a capability for manufacturing miniaturized precision mechanical components economically, but rather has traditionally relied upon foreign suppliers. Hence, the result of this situation has been that manufacturing equipment is not being developed or manufactured in the U.S. to satisfy this particular market. Further, because of this deemphasis, skilled and qualified personnel are rare and at a premium. Of course, all these factors tend to contribute to increasing the cost of manufacturing. In this context, information provided to the Committee stated that domestically manufactured gears cost 3¢ each versus 2¢ each for those imported from Europe. Since the gear cutting equipment is highly automated, it would appear that the 1¢ differential is attributable not only to higher direct labor costs but to differences in overhead burdens.

Hence, the quest is how to economically manufacture precision miniaturized pinion gears when bounded by the following constraints:

- Large government orders of 20 to 50 x 10^6 pinions per month.
- Limited non-government market. In the short term, government demand easily can exceed the non-government demand.
- Traditionally, minimum U.S. emphasis in this market.
- Impending technological shift from timers of mechanical vintage to completely electronic timer systems. This particular point is cogent to long-range industrial planners, since research and capital investment dollars will not be placed in an area that is likely to become obsolete.

B. SURVEY TO RESOLVE THE PROBLEM

In evaluating alternative approaches to manufacturing miniature precision pinions, a review of fuze pinion tolerances was made. Usually, in precision systems, tolerance control is exercised for the following two reasons:

1. Short-term positional or phase lag/lead control between input and output elements.
2. Minimization of dynamic loads resultant from mechanically induced errors.

The first objective has been quantitized as timing variations typically like 3σ deviations of 411 milliseconds in 60 seconds and 111 milliseconds in 3 seconds. Comments to the Committee indicate that present systems fall well within these 3σ limits. No dynamic loading information was given to the Committee nor is it commonly available. But, the Committee's industrial sources indicate a general lack of specific data relative to dynamic gear loads -- other than to indicate that preloads and operational loads could be substantial. The dynamic loads in gear teeth, due to mechanical errors such as total composite error, are illustrated in Figure 1.[1] Clearly, mechanical errors do contribute to increasing gear tooth loads; when designing in a marginal strength regime, the tendency is to "error" to the side of improved precision. Nevertheless, in summary, quantitative information is not available to the Committee relative to the dependency of timing errors and limit strength loads on the degree of mechanical errors such as tooth-tooth composite errors (TTCE), or total composite errors (TCE). Thus, the Committee is concerned with defining manufacturing alternatives that produce an equivalent quality pinion. In this context, Table I is presented to illustrate the precision capabilities of various manufacturing techniques.[2] Caution must be used in reviewing this table because the source of the data focuses on the more traditional gear sizes and not the miniaturized versions. Hence, in the category of fuze pinion sizes, one should upgrade each quality category, such as commercial to precision, and precision to ultra-precision. Therefore, fuze pinions appear dimensionally to be in the beginning

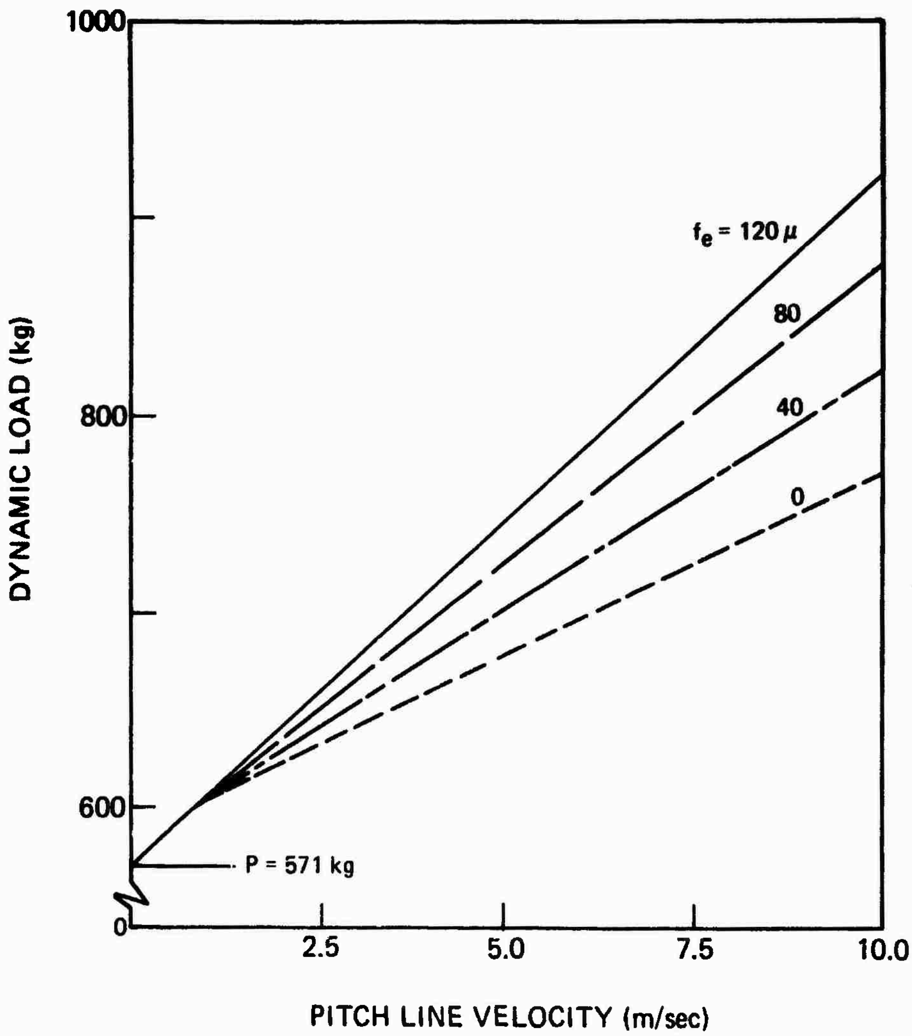

FIGURE 1 Dynamic gear tooth load as a function of base pitch errors (f_e).[1]

TABLE I Typical Tolerance Ranges (in inches) For Various Fabrication Processes[2]

Fabrication Process	General Quality Category	Tooth Surface Finish (μ in.)	Tooth Thickness Tolerance (+t/-0)	Maximum Total Composite Error	Maximum Tooth-to-Tooth Composite Error
Milling (form)	Commercial	12-63	0.001-0.003	0.001-0.003	0.0005-0.002
Hobbing	Precision	16-63	0.0003-0.002	0.0002-0.002	0.0002-0.0005
Shaping	Precision	16-63	0.0003-0.002	0.0005-0.002	0.0003-0.0007
Grinding	Precision	8-32	0.0002-0.001	0.0001-0.001	0.0001-0.0003
Shaving	Precision	16-32	0.0002-0.001	0.0002-0.001	0.0002-0.0004
Honing	Commercial	4-16	0.0005-0.002	0.0005-0.0015	0.0003-0.0007
Lapping	Commercial	4-16	0.001-0.002	0.001-0.003	0.0004-0.001
Burnishing	Commercial	8-16	0.001-0.003	0.001-0.003	0.0004-0.001
Stamping	Commercial	63-250	0.002-0.005	0.002-0.005	0.001-0.002
Drawing	Commercial	32-63	0.0015-0.005	0.0015-0.005	0.0005-0.002
Extruding	Commercial	32-63	0.0015-0.005	0.0015-0.005	0.0005-0.002
Die Casting	Commercial	63-125	0.002-0.006	0.002-0.006	0.001-0.003
Sintered powder	Commercial	32-125	0.001-0.003	0.0015-0.004	0.0007-0.0015
Nonmetallic, machined	Commercial	32-63	0.001-0.003	0.001-0.003	0.0004-0.0015
Nonmetallic, molded	Commercial	16-63	0.0015-0.005	0.0015-0.005	0.0005-0.002

precision class. The specified 32 to 63μ surface finishes are generally viewed as coarse for these stringent applications and fall within the commercial class.

From this short survey, alternatives available for large-volume, low-cost pinion manufacturing are:

1. Conventional machining
2. Drawing or extruding
3. Zinc die casting
4. Plastic molding
5. Powder metallurgy
6. Chemical etch/diffusion bond processing

In each case, what was sought was an existing technology with an appreciable civilian base to which the military could turn in an emergency. In the context of the survey, conventional machining is the present standard. Drawing or extruding has not generally been used for precision gearing because of the difficulty in maintaining good concentricity. This results because of distortion due to cold-working stresses and unsymmetrical strains and spring-back. It is possible to produce small pinions (in the precision class) with a 0.001-in. TCE and 0.0004-in. TTCE at surface finishes of 10μ. Of course, the operative requirement is cost--both from an operating and a die replacement standpoint.

Zinc die casting presents two problems. First, die cast materials have relatively low strengths for fuze applications. Second, zinc alloys for die casting can undergo long-term creep that can affect short-term timing accuracy as well as tooth dynamic loads. The effects of creep are important since the fuze gear train is under load for its storage period. Finally, to obtain precision quality, secondary finishing operations may be required.

Plastic molding has developed rapidly as a manufacturing process and new materials with improved properties are emerging. Of primary concern are the static strength and creep strength of plastics relative to fuze pinion requirements.

Powder metallurgy technology has been used to produce gears on the order of 0.001 to 0.002 in. TCE, 0.001 in. TTCE, and 0.001 to 0.002 in. tooth thickness. Usually, precision of this type is obtained by secondary deformation or machining operations.

Chemical etch/diffusion bonding has recently developed as a method for making intricate shapes such as fluidic elements and could be applied to the formation of pinion/gear components. Typically, parts are fabricated by diffusion bonding laminates whose shapes are controlled by photoetching. Procedures for separating individual parts from the multipart sheets would have to be developed.

The last four of the above mentioned alternatives were discussed by the Committee in order to define the specific advantages and shortcomings of each. Particular attention was paid to the economics of each method of manufacture. Subsequent sections of this report focus on specific details of these processes, the materials that would be suitable for each, the extent of pinion/gear redesign that might be necessary, the status of the technology necessary to implement the particular manufacturing process, and the approximate costs of producing pinions and gears by each process.

Little emphasis was given improvement of the conventional machining process since considerable expertise already exists and the primary goal of the Committee was to define alternatives to this process. However, some consideration was given to the possible easing of dimensional tolerances of conventionally machined pinions as a means for improving the economics of this method of manufacture and allowing a wider variety of equipment to be used in production. A subsequent section of this report indicates the manner in which the effects of dimensional tolerances in gears can affect gear train performance.

The drawing or extruding process for forming pinion cross-section rods to be used as feedstock for machining operations also was considered by the Committee. It was pointed out to the Committee that previous attempts to produce

pinions in this manner resulted in machining burrs on the pinion teeth, thus making the product unacceptable. Furthermore, rod twisting due to internal stresses, tooth-form accuracy, and stress tears also were problems resulting from the cold-work deformation process. Problems that occasionally occur, such as stress tears, could be eliminated by hydrostatic extrusion if good lubrication were achieved. There is limited present production of pinion stock (usually brass) by conventional extrusion. Mr. E. R. Cunningham (Cyclops Corporation), a special consultant to the Committee, pointed out that the high-strength specification on the Type 416 stainless steel used for pinions may be detrimental to drawing or extruding operations (135,000 psi minimum tensile strength is called for, but probably only about 80,000 psi is needed). The cold working necessary to achieve this strength may be detrimental to the drawing or extruding operation and also the subsequent machining operation. Furthermore, sulfur or selenium additions to stainless steel for improved machinability give rise to poor working behavior, especially in severe cold-work conditions. However, it is believed by the Committee that in spite of the fact that some improvements could be made in the drawing and extruding processes, the problems mentioned previously would probably more than offset any realized gains.

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I. ZINC DIE CASTING

A. INTRODUCTION

The die casting process was developed in 1849, but it was not until about 1929 that modern zinc die casting production began. It was then that zinc of 99.99 percent purity was developed. The success of today's zinc die casting depends on this high-purity metal. Prior to its development, die castings produced even from 99.95 percent purity were weak and brittle and deteriorated in use.

In the early 1930s, die casting used only about 10 percent of the total production of zinc metal while in recent years die casting accounted for over 40 percent of zinc metal tonnage. Increased automobile production coupled with greater use of die castings per car are a large factor in the upward trend. The inherent advantages of zinc die castings over other types of castings as well as other methods of fabrication accounts for the overall growth of the use of die cast zinc throughout industry.

B. PROCESS

Three methods for the fabrication of pinions using zinc die casting may be considered. The first method consists of casting the shaft, pinion, and gear together as a single unit. This is obviously the most economical process since no subsequent close tolerance assembly operation is necessary.

The second method consists of casting the shaft and pinion as a single part, followed by assembly with the brass gear. This method has the advantage of providing improved-quality gear teeth (strength and profile).

The third method consists of a process whereby the blanked brass gear and a pre-machined steel shaft are assembled by a zinc bonding operation that simultaneously forms the pinion. This process eliminates the need for the close press fit tolerances required for the accurate assembly of gears and pinions. The components to be assembled (blanked brass gear and pre-machined steel shaft) are positioned in a locating tool that maintains the required spatial relationship between the components and also contains a mold or cavity for the

injected metal (the cavity would produce the pinion). After the tooling is closed, a small amount of metal is injected into the cavity. As the metal solidifies, shrinkage occurs to lock into undercuts and grooves designed into the parts being joined.

The first two methods, although possibly more attractive economically than the third, are believed to have technical drawbacks. In the first method, die casting of gear teeth would be difficult due to their small size; mechanical failure of these teeth would be a problem. In the second method, the formation of a high-strength joint between the cast pinion and the blanked brass gear would be a problem. The high operating stresses might make this location the site of primary operating failures. In both of these processes, the strength of the zinc pivots may be inadequate. Thus, the remainder of this section of the report deals with the third fabrication method -- the zinc bonding of blanked brass gears and pre-machined steel shafts with the bond region being cast in the form of the pinion.

C. MATERIALS

Only zinc die casting alloy compositions for which considerable technological experience exists were considered for this application. Composition specifications for Zamak #3 (ASTM AG40A or SAE 903) and Zamak #5 (ASTM AC41A or SAE 925) are covered by ASTM specification ASTM B-86-64 and are presented in Table II along with typical properties of die castings produced from these alloys.

TABLE II Properties of Zinc Die Casting

(Specification ASTM B-86-64)		Zamak #3 (ASTM AG40A) (SAE 903)	Zamak #5 (ASTM AC41A) (SAE 925)
	Chemical Composition in % by weight		
Composition % by Weight	Copper	0.25 max.	0.75 to 1.25
	Aluminum	3.5 to 4.3	3.5 to 4.3
	Magnesium	0.020 to 0.05	0.03 to 0.08
	Iron Max.	0.100	0.100
	Lead Max.	0.005	0.005
	Cadmium Max.	0.004	0.004
	Tin Max.	0.003	0.003
	Zinc (99.99+ % purity)	Remainder	Remainder

Typical Properties

	Zamak #3	Zamak #5
Charpy impact strength, (ft-lb, $\frac{1}{4}$ x $\frac{1}{4}$ in. bar, as cast)	43	48
Charpy impact strength, (ft-lb, $\frac{1}{4}$ x $\frac{1}{4}$ in. bar, after 10 yrs indoor aging)	41	
Charpy impact strength, (ft-lb, $\frac{1}{4}$ x $\frac{1}{4}$ in. bar, after 20 yrs indoor aging)	39	20
Tensile strength, (psi as cast)	41,000	47,600
Tensile strength, (psi after 10 yrs indoor aging)	35,000	
Tensile strength, (psi after 20 yrs indoor aging)	33,000	36,000
Elongation, % (in. 2 in. as cast)	10	7
Elongation, % (in. 2 in. after 10 yrs indoor aging)	16	
Elongation, % (in. 2 in. after 20 yrs indoor aging)	20	12
Expansion (growth), (in. per in. after 10 yrs indoor aging)	0.0000	
Expansion (growth), (in. per in. after 20 yrs indoor aging)	0.0000	-0.0001
Brinell hardness	82	91
Compression strength, (psi)	60,000	87,000
Modulus of rupture, (psi)	95,000	105,000
Shearing strength, (psi)	31,000	38,000

D. DESIGN

A modest alteration of the pinion/gear assembly will be necessary to take advantage of the potential of the zinc bonding process and to offset difficulties that may arise due to the relatively low strength of zinc die casting alloys and problems in achieving good mechanical interlocking between the cast pinion and blanked brass gear.

The recommended design of the pinion involves the addition of a flange at the end near the gear, as shown in Figure 2. The flange would primarily strengthen the pinion teeth and secondarily aid in the bonding between the pinion and gear.

The close tolerance hole presently used in gears to be assembled to machined pinions would not be necessary. However, the hole pattern would have to be designed to provide keying with the pinions during the die casting assembly operation. While injected metal shrinkage would mechanically lock the assembly together, gear hole features would have to be designed to provide strength to withstand service loads. For example, annular grooves would be poor since they would not resist torque loads; straight or diamond knurling would be recommended. Other forms of locking surfaces such as undercuts, lugs, or dovetails also could be considered. (Since the bonding involved is mechanical, not chemical, the components involved--blanked brass gear and pre-machined steel shaft--should not require chemical cleaning or fluxing but should be free of grease and any foreign material.)

Dimensional tolerances are certainly of prime importance in the casting of the pinions. Under normal circumstances in zinc die casting operations, tolerances to $\pm$ 0.003 inches per inch (length or diameter) are obtainable. For conditions that require even closer dimensional control, tolerances down to $\pm$ 0.001 inches per inch are possible by careful equipment and process control. Zinc die castings can be produced with a minimum wall thickness of 0.015 inches. These tolerances appear to be adequate for pinion manufacture.

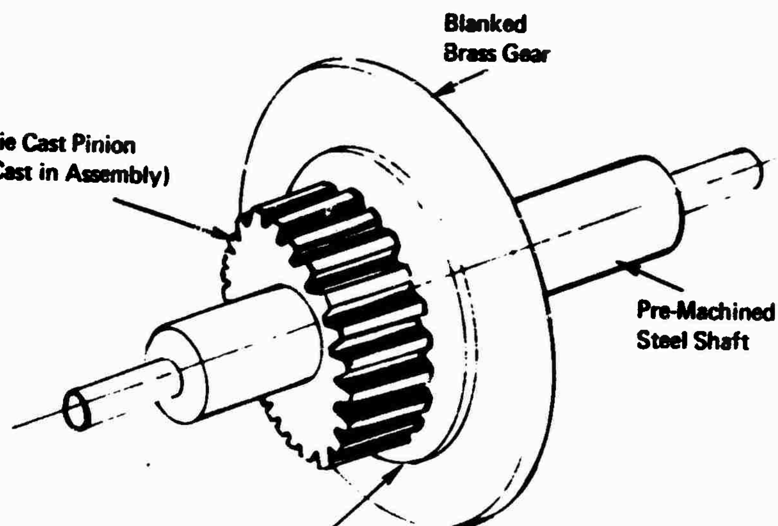

FIGURE 2 Pinion/gear assembly produced by zinc die casting process.

Two factors that affect die casting accuracy are erosion of the die casting surfaces and solidification shrinkage. As the number of castings made in a particular die increases, the die surface progressively degrades and the dimensional accuracy of the part decreases. Since the cast part shrinks as it cools, care must be taken to insure process uniformity from part to part to provide for constant amounts of shrinkage.

E. TECHNOLOGY STATUS

Although numerous industries use the die casting process, only a selected few offer the skills and equipment sophistication necessary to produce products equal in quality to those required in the successful production of miniature high-tolerance parts.

One such company is the Gries Reproducer Corporation, located in New Rochelle, New York. This company has had over 25 years of experience in the high-volume production of miniature close-tolerance parts.

Another company highly experienced in the production of automated assembly equipment for high-speed assembly of small parts by the zinc die cast process if Fisher Gauge, located in Peterborough, Ontario, Canada. Approximately 45 U.S.-based industries and about 85 foreign countries are presently using assembly equipment developed by Fisher Gauge.

No special skills are necessary to operate this type of equipment; operators may be trained very quickly.

F. COSTS

Since the configuration and quality of the casting die dictates the product quality obtainable, subsequent machining operations are virtually unnecessary. Generally, savings in machining and finishing will amortize the costs of casting dies over production runs in the low thousands. Scrap loss is extremely low (as little as 2 to 4%) since sprues, gates, and flash can be reused.

Assembly equipment of the type necessary in this manufacturing process presently costs approximately $25,000 per unit. An additional cost of approximately $10,000 per unit would be required for necessary tooling.

Since the feeding of blanked brass gears and machined steel shafts would be completely automatic, a production rate of approximately 800 to 1,000 pieces per hour could be realized.

The following are approximate costs:

$87 per 1,000 in lots of 5,000 pieces

$25 per 1,000 in lots of 100,000 pieces

$20 per 1,000 in lots of 500,000 pieces

$18 per 1,000 in lots of 1,000,000 pieces

G. CONCLUSIONS

1. Fabrication of pinion/gear assemblies by a one-step zinc die casting operation, although attractive from an economical point of view, would probably result in gear tooth problems during production and/or service.
2. Fabrication of pinion/gear assemblies by assembling blanked brass gears to a zinc die cast pinion (including the shaft) would probably result in service failures at the joint between the gear and the pinion.
3. Zinc die cast bonding of blanked brass gears and pre-machined steel shafts along with simultaneous casting of the pinion could prove to be an attractive method for producing pinion/gear assemblies. Design tolerances and economics do not seem to be a major problem for this process; however, careful technical evaluation of the product would be necessary.

II. PLASTIC MOLDING

A. INTRODUCTION

A preliminary overview of the applicability of plastics as a substitute for stainless steel in fuze pinions suggests that this would not be feasible if the more common materials and typical methods are employed. Plastic pinions would have to meet stringent dimensional and mechanical load criteria beyond those normally associated with injection-molded plastic parts. Additionally, certain environmental problems (such as creep, temperature and solvent resistance) that presently are of little importance in metallic pinions could be expected to arise.

However, by placing extraordinary controls on machine operation, the parts produced could be held to a reduced scatter on dimensions. Careful selection of the plastic material could raise the mechanical properties close to those required for this application. (It is of interest in this regard that an advertisement for injection-molded plastic gears for watches appears on p. 35 of New Scientist, November 1, 1973.)

B. INJECTION MOLDING

The basic process considered in this study for forming thermoplastic materials into shaped parts was the injection-molding technique.

In essence, pellets of the plastic material are fed into the hopper of the machine and then are transported by a screw through a heated barrel. During the transport through the injection-machine barrel, the plastic material is exposed to heat and pressure that causes the plastic to soften into a pliable mass. The hot, pliable mass of plastic accumulates in front of the screw, and when a sufficient charge is accumulated, the screw stops rotating and acts as a hydraulic plunger to force the softened plastic into a relatively cool mold. The cool mold causes the resolidification of the plastic, thus forming the desired shape.

C. MATERIALS

The materials considered for this application were primarily glass-fiber-filled thermoplastics such as:

1. Glass-filled polycarbonate
2. Glass-filled nylon
3. Glass-filled polyester

D. DESIGN

One reason the application of plastic materials has grown at a tremendous rate is that they can be made so that they can perform more than one function (e.g., electrical insulation and mechanical support, structural support and decorative capability, low cost and intricate design). However, there has been no single, significant application that did not require the redesign of the part, previously made in another material, in order to facilitate its economic production in a plastic. Unless one takes the time and effort to design the part for the plastic material to be used, then it is quite likely that an unsatisfactory application will ensue.

This seems to be the case with plastic pinions for artillery shell fuzes for which principal concerns are creep strength and fracture strength. Unless the system can be redesigned to limit the stresses substantially below about 30,000 psi, the use of plastics does not seem reasonable. The long-term (creep) stress level would need to be limited to below 5,000 psi.

E. TECHNOLOGY STATUS

During recent years use of thermoplastic injection molding has increased tremendously, and probably no major U.S. corporation is not involved in the injection-molding process to some degree. Therefore, one can expect that a vast pool of plastics expertise will exist in the United States in the foreseeable future.

Moreover, there has been a continued striving to use plastic materials in an engineering sense. That is, there is a growing awareness of the potential

of these materials, and investigative programs related to process control and part uniformity are well under way in many industrial facilities. A major strength in the use of plastics in artillery fuzes would be this strong and ever-growing technological and productive industrial base.

F. EVALUATION PROCESS

1. Physical Dimension

Probably the first reaction encountered when discussing the dimensional tolerances associated with the pinion/gear assembly is that requirements are beyond the state of the art for injection molding. That statement is true for the most part, considering the average plastic-molding facility; however, a substantial amount of investigative work, particularly over the past five years, has indicated that the proposed dimensional tolerances can most likely be met by modifying present equipment. These modifications would include revision of portions of the hydraulic control system and modification of the basic process control devices now used on most injection-molding machines.

For example, the 3_σ standard deviation limits on length in producing an 8-inch tensile bar are:

Before Machine Modification: $\pm.003$ in.

After Machine Modification: $\pm.0007$ in.

It should be noted that the $\pm.0007$-in. tolerance range was made on a part of substantial length, but data of the same basic type were obtained in a second, unrelated, test program in the same company. In addition, at least one product manufacturing operation is known to be operating a high-volume facility in which plastic parts in the improved tolerance range noted are being produced by injection molding.

While this does not guarantee that the production of precision parts by injection molding is an on-going, universally achievable process, it is good evidence that such a process has the capability of doing the job under the right circumstances of process control, environment, machine/mold design, and equipment maintenance.

2. Creep with Time

Injection-molded thermoplastic changes dimensions when a steady load is applied and maintained. The relatively low modulus of elasticity (200,000 to 1,500,000 psi compared to 30,000,000 psi for steel) indicates that elastic strains under static loads will be considerably larger than for metallic gears. In addition, the plastic materials tend to creep under a long-term loading condition. Creep rate is dependent (for any one material) upon the applied stress level, the storage temperature, the condition of the molding with respect to molded-in stress, and the effect of other environmental conditions (solvents, for instance).

It is quite possible that one of the main failure mechanisms that would prohibit the use of plastic pinions in artillery fuzes is related to this creep phenonomena. However, since relatively few creep data for small, relatively stress-free parts exist in the literature, a test program would be required to determine the suitability of fiber-reinforced materials for the pinion application.

3. Stress

The short-term published flexural strength of a 40 percent glass-filled polycarbonate, or polyester, is about 30,000 psi. It is believed an idealized compound that would yield a flexural strength of, perhaps, 35,000 psi could be molded. However, a report from Picatinny Arsenal (Evaluation of Plastic Materials for M125A1E4 Booster Gear and Pinion -- John Nardone, June 1970) indicates that bending stress levels in the pinions caused by the artillery shell rotation exceeds the maximum strength of the glass-reinforced thermoplastic material above 20,000 rpm (Table III).

G. PRODUCTION COSTS

If one assumes that technical and environmental problems are fully satisfied, then the issue of cost for a molded plastic pinion must be considered.

The weight of a typical pinion (e.g., the #3 pinion) is about 0.17 grams. Assuming no change in dimensions, a fiber-filled plastic pinion would weigh about

TABLE III Pinion Stresses* (M125A1E4 Booster Gear and Pinion)

RPM	Stress (#/in.^{2}) On Center Rotation	Stress (#/in.^{2}) Off Center Rotation
5,000	1,640	2,140
10,000	6,540	8,500
15,000	14,800	19,300
20,000	26,300	34,200
25,000	41,200	53,500
30,000	59,300	77,000
33,000	72,300	93,000

* Data taken from Picatinny Arsenal Technical Memorandum 1918

0.03 grams. At a cost of about \$1.00 per pound for an engineering plastic (polycarbonate, for instance), the material cost for a pinion is 0.006¢. If sprues, runners, and other scrap are not reusable, material use could be 50 times that estimated, or 0.3¢ per pinion.

Based upon the use of small, automatic injection-molding machines, a 10-cavity mold, an operating charge of \$30 per hour for labor and eqiupment, and a cycle time of 15 seconds, the manufacturing cost per item will be 1.2¢. Thus, the total cost of a pinion/gear assembly would be about 1.5¢.

These estimates are reasonable enough to indicate the order of magnitude of production costs. Costs for tooling are not included, but they would not significantly affect part costs on large volume orders.

H. FEASIBILITY COSTS

Assuming the fuze mechanism can be redesigned to reduce the bending stress during firing to about 15,000 psi and the long-term load on the gear to less than 5,000 psi, development costs for establishing molding parameters, mold design configuration, and machine modification requirements on a "demonstration of feasibility" basis most likely would range between \$30,000 to \$50,000.

I. INDUSTRIAL FACILITY COSTS

If one assumes that 10 parts are made during each molding cycle, that the cycle is 15 seconds long, and that operations are on a three-shift/seven-day basis, capital equipment costs will be between \$750,000 and \$1,000,000 for precision molding machines and controls required for the production of 20×10^6 pinions per month.

J. CONCLUSIONS

1. Artillery shell fuze pinions most likely can be produced by injection molding to meet the dimensional specifications of the application.

2. It is expected that the cost of such an injection-molded pinion would be no greater than that of a present pinion and that it is quite likely a reasonable cost savings could result.
3. Because of the high creep load due to long-term spring tension and the high bending stress caused by shell rotation, there are grave doubts that a direct substitution of plastic material for the currently used steel can be made.
4. To allow the use of injection-molded thermoplastic in this application, a redesign of the fuze mechanism is required to reduce the stress levels in the pinion assembly.
5. Capital equipment costs for precision machines to produce 20×10^6 pinions per month would not exceed $\$1 \times 10^6$.

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III. POWDER METALLURGY

A. INTRODUCTION

Powder metallurgy (PM) is a process for producing metal or alloy parts by blending powders, compacting the blended powders (usually under pressure in a closed die cavity) to the required strength, and sintering the compact in a controlled atmosphere in order to bond the particles together. Some parts are subsequently coined, repressed, impregnated with oil or plastic, infiltrated with a lower melting metal or alloy, heat-treated, and given desired finishing operations.

The raw materials in PM processing consist of size-controlled metal powders of specified shape. These powders may be blended with lubricants, graphite, or other additions. The blended powders are loaded into precision closed dies and compressed between punches in hydraulic or mechanical presses. In the case of multilevel parts (e.g., fuze pinions), more than one processing level is needed, and multiple punches and separate actions are required in the die and press installations, respectively. After compaction, the parts are sintered in a continuous furnace, under protective atmosphere, at temperatures typically greater than two thirds of the absolute melting point of the major component. Under these conditions, diffusion and recrystallization processes effect the bonding of particles; in the case of iron or steel PM, the atmosphere composition is also controlled to obtain the desired carbon content. After sintering, the parts may be directly used or further processed, as by coining (i.e., slight deformation in a die) for close dimensional tolerances or by impregnation or infiltration.

The chief advantages of PM processing are that:

1. Little or no machining or finishing operations are necessary
2. Production rates are high
3. Flexibility in achieving compositions unattainable by conventional melting, casting, and working operations is offered
4. Density of the part can be controlled

B. PROCESS

The PM process envisioned for production of fuze pinions is a standard press-and-sinter operation followed by a coining operation to achieve required dimensional tolerances.

A three-component assembly is recommended for the pinion/gear combination:

1. Pinion-- PM fabrication as a two-level part having a hollow center; the smaller diameter region would accommodate the gear and the hollow center would accommodate the shaft whose ends serve as pivot points
2. Gear-- PM fabrication as a one-level part or a blanked brass gear as is presently used
3. Shaft-- machined from steel rod on a high speed screw machine

The overall assembly is shown schematically in Figure 3. The splines on the gear would be fitted into mating splines molded into the PM pinion. The machined steel shaft not only would provide the wear-resistant pivots, but also a means for assembling the pinion and gear and, possibly, an additional means for strengthening the joint between the pinion and gear.

Tolerances on parts produced by standard press-and-sinter operations would be marginal for the intended application. The subsequent coining operation, however, should permit achievement of required tolerances.

The decision as to whether the gear should be PM fabricated or blanked from a brass sheet would be made after a technical feasibility study and a detailed economic analysis were carried out. The design of this gear would be essentially the same for either manufacturing process.

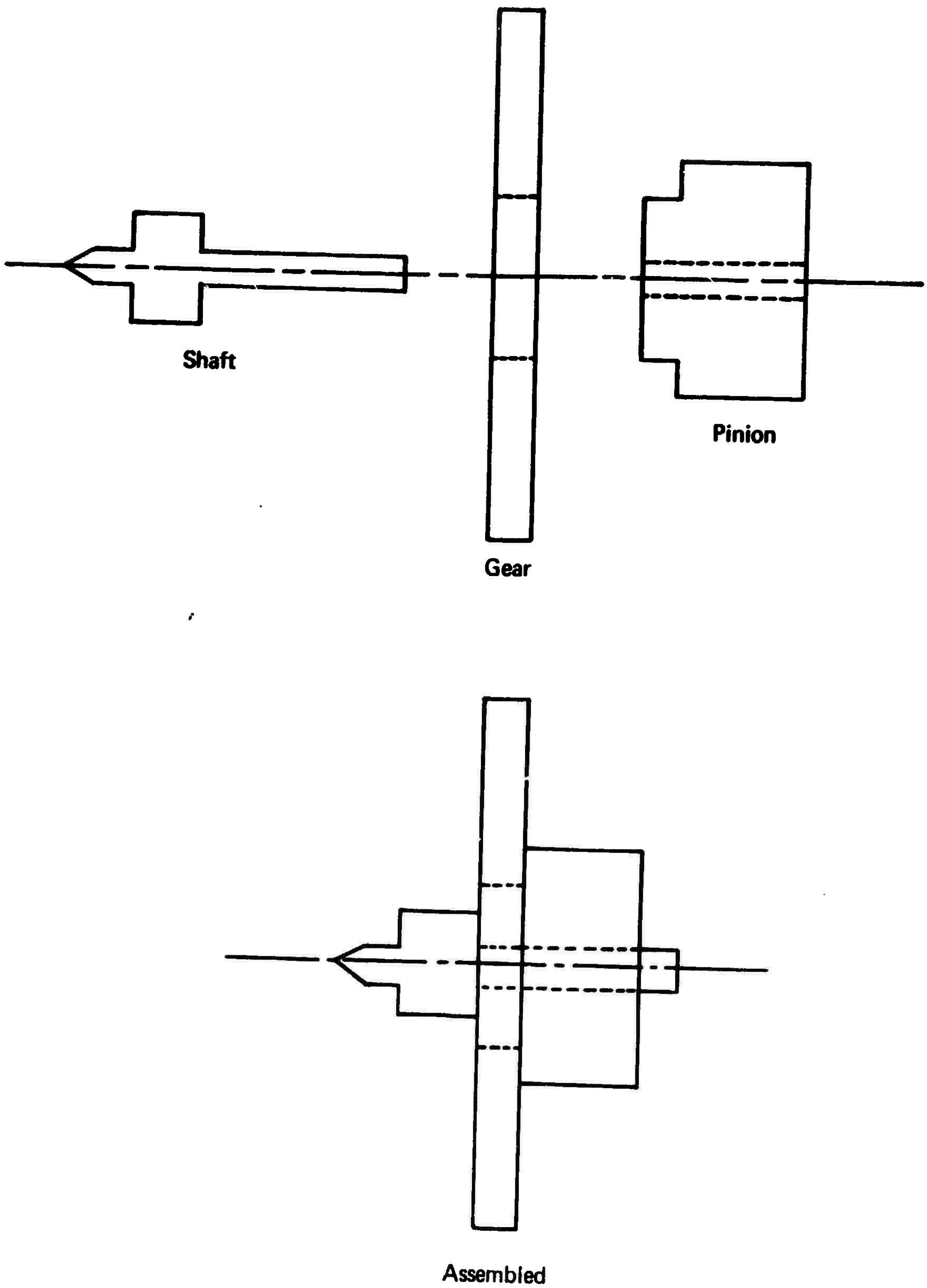


FIGURE 3 Pinion/gear assembly produced by powder metallurgy process.

C. MATERIALS

A range of prealloyed powders is available for the production of gears and pinions. Brass, bronze, and stainless steel powders are produced commercially, tailored alloy compositions also can be made to meet special requirements. Some development effort would be necessary to define the optimum powder composition necessary to meet strength and corrosion resistance requirements and to assume minimum die wear during compaction. However, it is anticipated that effort required would not be great. (It might also be meaningful to consider non-metallic powders, e.g., polyimides.)

D. DESIGN

The conversion from fabrication by machining to fabrication by PM typically involves consideration of technical and economic factors related to part design. The proposed three-component assembly process should greatly minimize the extent of design alteration to the overall pinion/gear composite.

E. TECHNOLOGY STATUS

The PM industry is well established and is developing fairly rapidly in both size and range of applications. A current list of manufacturers is available (PM Parts and Equipment Manufacturers Directory, Precision Metal, January 1973, pp. 206-245). Parts of the type and size considered in this report are not uncommon to PM manufacturers; the types of alloy being considered also are not uncommon. However, some process development for the application intended would obviously be necessary in order to assure meeting dimensional tolerances economically.

F. COSTS

Even considering the coining and assembly operations that would be necessary, pinion/gear assemblies of the designs typically used in artillery fuzes probably could be manufactured in large lots at competitive costs (i.e., 2¢ to 3¢ per assembly). Since a well established industry already exists, basic process development costs for large-scale production should be minimal;

however, process feasibility study costs would be necessary.

G. CONCLUSIONS

1. Powder metallurgy fabrication of artillery fuze pinions and, possibly, gears appears to be a meaningful alternative to present practice in regard to both technical and economic factors.
2. Some development work would be necessary to establish the details of the PM process (alloy compositions, powder characteristics, press-sinter-coin variables, method of assembly, etc.). This work also would define the exact nature of possible redesign that would be necessary to utilize the PM process.
3. Product evaluation studies would be a logical part of the above mentioned development program. Of primary importance would be the economic factors associated with achievement of dimensional tolerance, surface finish, and pinion/gear assembly properties.

IV. CHEMICAL ETCHING AND DIFFUSION BONDING

A. INTRODUCTION

Chemical-etching procedures have been long used in the manufacture of printed circuit boards for electronic application. Chemical-milling procedures also have been used in the airframe industry to reduce the weight of structural components by means of metal removal from discrete locations without affecting the overall structural strength of the member.

More recently, the chemical etching procedure has been combined with a metal diffusion technique to produce small parts composed of discrete laminae metallurgically bonded together into a solid, precision metal part.

B. THE BASIC PROCESS

The physical size of the pinion of interest is substantially smaller than that of the laminated parts that have been made on an industrial basis to date. However, it is not impractical to consider the same basic processing steps that have been used to date.

The first step in the process would be to pass the sheet steel (0.003 in. to 0.004 in.thick) through a suitable flattening system. A coating of a photochemically active material would be applied by a spray or immersion system. By conventional processing techniques the photo-resist coating would be cured in the required pattern, and the sheet would be passed through a chemical etching bath where the metal-removal step would take place. Upon completion of the metal-removal process, the remaining photo-resist coating would be chemically removed. The resulting product would be a sheet of "punchings" held together at four points by small connecting metal fingers (Figure 4).

Assuming that the sheets are sized to accommodate about 1,000 individual laminations, between 20 and 40 such sheets may be assembled on supporting mandrels and placed in a vacuum furnace. With the application of suitable heat and pressure, the individual sheets of lamination become bonded together into a solid mass of interconnected pinions.

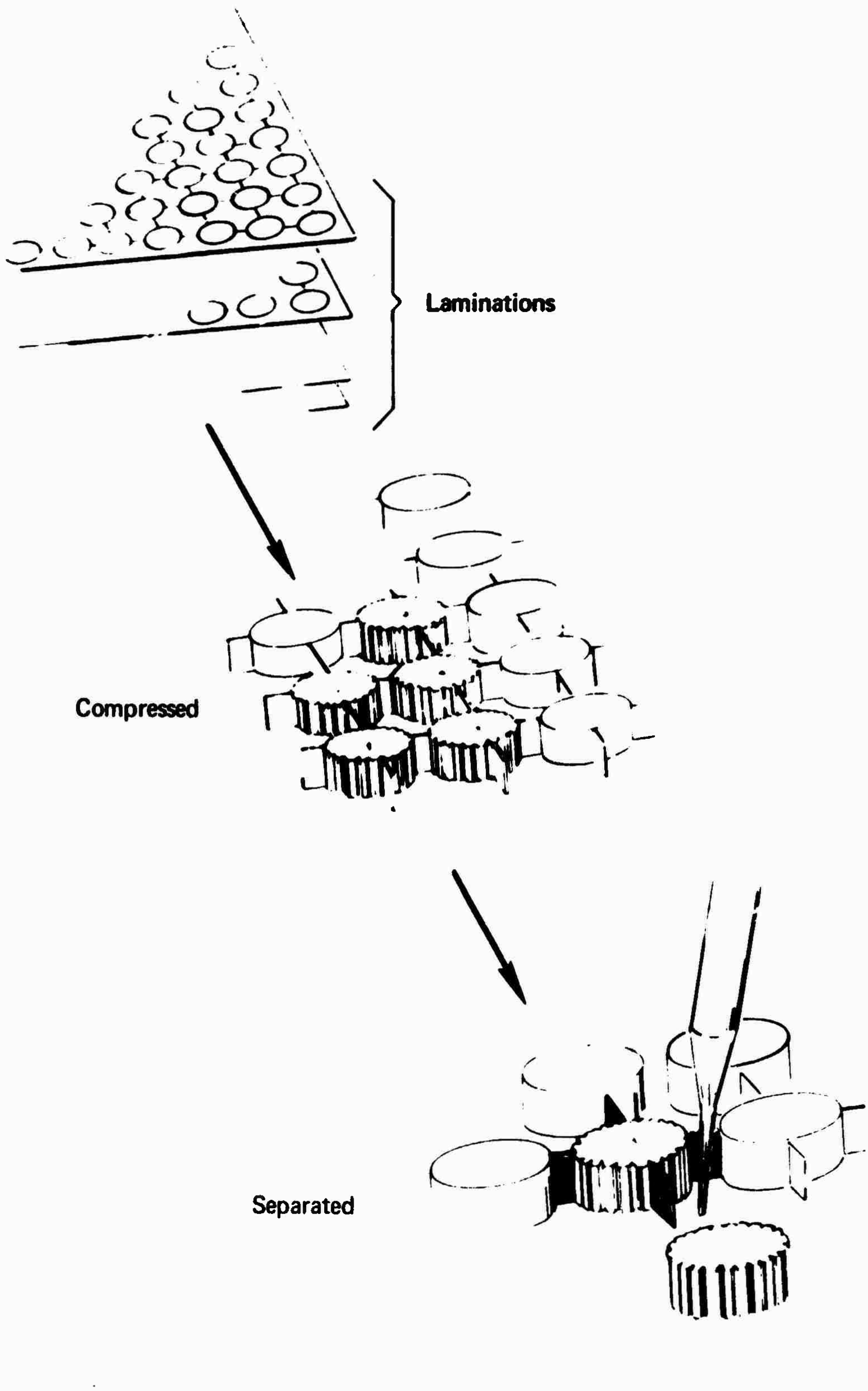


FIGURE 4 Chemically etched pinions.

The next step in the process, and the one frought with the highest degree of uncertainty, would be the separation of the individual pinions from the master sheet. Careful attention would have to be given to developing a suitable method for separating the individual pinions without damaging the shape. Electrical discharge machining is one candidate process for separating the pinions from the sheets.

C. MATERIALS

Almost any metallic material can be used in producing pinions by the chemical-etching, stacked-lamination technique, and the presently used stainless steel has proven satisfactory, there seems little reason to change. It is possible that some other stainless steels would have superior etching characteristics, but as of the present time, the material selection does not seem to be a limiting factor in the process.

D. DESIGN

No fundamental design change in the pinion configuration is anticipated at this time because of process requirements.

E. TECHNOLOGY STATUS

The basic chemical-etching technology associated with this process is widely used throughout the United States. The diffusion bonding and electrical discharge machining procedures also are widely used in the United States. All equipment associated with the process is available in the United States.

While the required dimensional accuracy for the pinions will put a heavy burden upon the automation of the laminate-production, stacking, diffusion-bonding, and separation machinery, it is believed that the pinions can be manufactured within the necessary dimensional requirements.

F. PROCESS EVALUATION

It is believed that the fundamental chemical-etching process has the potential of producing pinions that are at least equivalent in strength and cost to the present machined pinions. Several basic problems do exist, however, and they must be resolved by development studies.

The first known technical problem is related to the precision of alignment of the sheets that can be achieved during the stacking and diffusion-bonding operation. And, of course, it must be demonstrated that the individual etched lamination can be held to the desired tolerance. Experience indicates that satisfactory results can be expected.

A second basic problem that must be resolved is the means of detaching the individual pinions from the "mother assembly" (Figure 4). Possible steps necessary to achieve this separation without damaging the pinion/gear teeth have been considered, but unfortunately none of these techniques (described below) have been applied to parts of similar physical dimensions having the tolerance requirements of the proposed application. A more detailed study and process development program is quite likely to uncover other techniques that would be successful in removing pinions from the "mother assembly" and/or removing possible rough surfaces.

1. Separation of Pinions by Multi-spindled, Electrical Discharge Trepanning

In this approach a series of hollow rod electrodes would surround each individual pinion and, in a trepanning fashion, electrically erode the four connecting metal fingers holding the assembly to the master sheet of pinions. It is believed that this technique, if carried out in a controlled fashion, will release the individual assemblies without creating an unreasonable effect upon the tooth profile.

2. Removal of Possible Rough Surfaces by Thermal Deburring

Thermal deburring is a process wherein a burr-containing part is exposed to a burst of thermal energy of very short duration. The small mass

a charge of hydrogen and oxygen is introduced and then detonated by spark discharge. In less than a millisecond the reaction is completed with an instaneous shock wave temperature of 6,000 °F. The process has been used to deburr zinc, plastic, and steel parts and should be applicable to deburring diffusion bonded pinions.

G. INSERTING SHAFT

A problem exists with respect to the insertion of the required shaft into the bonded pinion block assembly. It is expected that the shaft would be made on a modified screw machine device and diffusion bonded during the laminate-bonding step. An alternate assembly route would use the shaft as a mandrel to pick up individual laminations prior to the diffusion-bonding step. If this latter approach is used, the need for a separation step would not be required.

H. ADVANTAGES

A singular advantage of the multi-laminated pinion is the great likelihood that a stronger gear tooth will result. Using a staggered stacking technique no possibility of grain orientation or flaws in the pinion tooth is likely to exist.

I. PRODUCTION COSTS

The process requires a certain amount of development activity to bring it up to a satisfactory state for production purposes. However, it can be a highly automated manufacturing system with a low labor requirement. There is reason to believe that the direct labor and direct material costs would total less than 0.5¢ per pinion.

J. FEASIBILITY COSTS

Feasibility study costs are expected to be between \$60,000 and \$75,000. The net results of such a study would be a good definition of the production facility and could include the production of several hundred pinions by non-automatic means to establish basic process feasibility.

K. INDUSTRIAL FACILITY COSTS

It is expected that the basic capital equipment costs for an automated production facility capable of producing 20×10^6 pinions per month would be between \$1,750,000 and \$2,000,000.

L. CONCLUSIONS

1. Artillery shell fuze pinions most likely can be produced by chemical etching thin laminates and diffusion bonding an assembled stack of laminae into a solid pinion body.
2. It is anticipated that such a pinion will not exceed present costs on a direct labor plus direct material cost basis but may exceed present costs if equipment depreciation costs are included and a short depreciation period is used.
3. All of the major process steps are carried out rather extensively in the United States using U.S. produced equipment.
4. No redesign of the pinion is required, and superior tooth strength might be achieved.
5. Several of the process and automation steps require development effort before the manufacturing process can be fully defined.
6. Capital equipment costs to produce 20×10^6 pinions per month are expected to be less than \$2,000,000.

V. GEAR TRAIN DESIGN

A. GEAR TRAIN SIMULATION

In the design and development of precision gear timing systems, it is well within the capability of standard practice to predict the potential performance of a gear train design prior to the build and test stage. The establishment of a predictive design model provides an economical tool for quantitatively comparing competitive design alternatives and for establishing the probability of attaining the design specifications with any of the proposed designs. In this way, a measure is obtained of how sensitive the gear design must be to achieve satisfactory total system performance. For the problem of fuze timing gear trains, the specification has been set at a 3σ deviation of 411 milliseconds in 60 seconds and 111 milliseconds in 3 seconds. Dynamic loading is not specified except to state that the system must survive all firing-cycle loads. The dynamic loads in a running gear mesh are shown to be affected by various gear dimensional errors, and Figure 1 (p. 3) illustrates how increasing gear errors produce a corresponding increase in the dynamic tooth load.[1] Hence, when designing in a marginal regime, the dynamic load predictions are obtainable.[1-3]

Once it has been decided that a particular gear set can survive the dynamic loading environment, the timing errors can be predicted by first establishing the potential dimensional deviations in terms of average amplitudes and cycle frequency characteristics. The gearing errors of interest are those that affect the basic gear tooth action and the instantaneous gear transmission ratios. Table IV illustrates the average tooth-to-tooth errors associated with fine pitch gearing, and Table V lists the potential backlash on tooth-to-tooth clearance as specified by AGMA. When these average errors are assumed to represent the amplitude for cyclic deviations in the effective gear ratios, the instantaneous transmission ratio is predictable by simple arithmetic calculations of the ratio of the instantaneous pitch radius of each meshing gear. This approach produces the maximum possible error, but not the frequency at which it occurs. Figure 5

TABLE IV AGMA Backlash Allowance and Tolerance For Fine Pitch Gears

Backlash Designation	Normal Diametral-Pitch Range	Tooth Timing to Obtain Backlash		Resulting Approximate Backlash (per mesh) Normal Plane
		Allowance (per gear)	Tolerance (per gear)	
A	20 through 45	0.002	0 to 0.002	0.004 to 0.008
	46 through 70	0.0015	0 to 0.002	0.003 to 0.007
	71 through 90	0.001	0 to 0.00175	0.002 to 0.0055
	91 through 200	0.00075	0 to 0.00075	0.0015 to 0.003
B	20 through 60	0.001	0 to 0.001	0.002 to 0.004
	61 through 120	0.00075	0 to 0.00075	0.0015 to 0.003
	121 through 200	0.0005	0 to 0.0005	0.001 to 0.002
C	20 through 60	0.0005	0 to 0.0005	0.001 to 0.002
	61 through 120	0.00035	0 to 0.0004	0.0007 to 0.0015
	121 through 200	0.0002	0 to 0.0003	0.0004 to 0.001
D	20 through 60	0.00025	0 to 0.00025	0.0005 to 0.001
	61 through 120	0.0002	0 to 0.0002	0.0004 to 0.0008
	121 through 200	0.0001	0 to 0.0001	0.0002 to 0.0004
E	20 through 60	Zero	0 to 0.00025	0 to 0.0005
	61 through 120		0 to 0.0002	0 to 0.0004
	121 through 200		0 to 0.0001	0 to 0.0002

Extracted from AGMA, Gear Classification Manual, AGMA 390.02.

TABLE V Fine Pitch Tolerances for AGMA Quality Classes

AGMA Quality No.	Number of Teeth and Pitch Diameter	Diametral-Pitch Range	Tooth-to-Tooth Composite (Error) Tolerance	Total Composite (Error) Tolerance
13	Up to 20 teeth inclusive	20 to 200	0.0003	0.0004
	Over 20 teeth up to 1.999 in.	20 to 200	0.0002	0.0004
	Over 20 teeth 2 to 3.999 in.	20 to 200	0.0002	0.0004
	Over 20 teeth 4 in. and over	20 to 200	0.0002	0.0005
14	Up to 20 teeth inclusive	20 to 200	0.00019	0.00027
	Over 20 teeth up to 1.999 in.	20 to 200	0.00014	0.00027
	Over 20 teeth 2 to 3.999 in.	20 to 200	0.00014	0.00032
	Over 20 teeth 4 in. and over	20 to 200	0.00014	0.00037
15	Up to 20 teeth inclusive	20 to 200	0.00014	0.00019
	Over 20 teeth up to 1.999 in.	20 to 200	0.00010	0.00019
	Over 20 teeth 2 to 3.999 in.	20 to 200	0.00010	0.00023
	Over 20 teeth 4 in. and over	20 to 200	0.00010	0.00027
16	Up to 20 teeth inclusive	20 to 200	0.00010	0.00014
	Over 20 teeth up to 1.999 in.	20 to 200	0.00007	0.00014
	Over 20 teeth 2 to 3.999 in.	20 to 200	0.00007	0.00016
	Over 20 teeth 4 in. and over	20 to 200	0.00007	0.00019

Extracted from AGMA, Gear Classification Manual, AGMA 390.02.

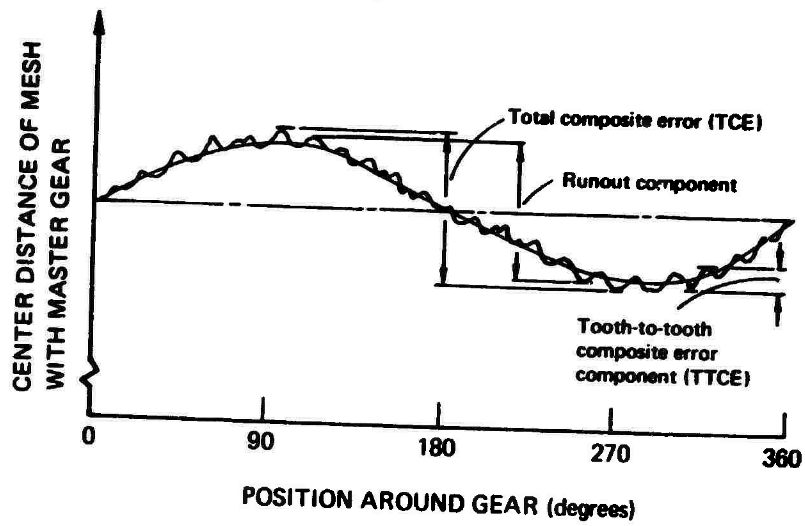


FIGURE 5 Gear set transmission errors.[3]

shows how these errors add to produce gear mesh phasing errors.

The term "average error" has been employed because it is well known that in a large population of gears, gearing errors are statistically distributed about some mean. The means for each type of error, are typically specified in the AGMA Standards. Figure 6 illustrates how the mean and standard deviation of a typical gear error are related to a range of maximum total composite errors. In the simulation, if the average errors are modified by some multiple of their respective standard deviations, the mean and standard deviation of the total transmission ratio can be determined as a measure of the statistical variability of a family of gear sets selected from a population of gears with known statistically distributed errors. In this way, a design can be evaluated from the point of view of what percentage of similarly constructed units will meet the timing goal of the earlier described 3σ limits. As a point of illustration, an example is included in Appendix A. For this case, a simple gear set is driven by an electric motor and the driven load is a simple inertia element. Average cycle gear errors resultant from run-out and gear tooth errors are evaluated in conjunction with bearing run-outs and torque variations. A statistical analysis was not undertaken here, but a simple modification of these average error values to include the respective standard deviations would yield what percent of the total population is compatible with the design goals.

B. CONCLUSION

Simulation of gearing systems is at a well developed state. Today it is possible and practical to evaluate dynamically the value gear transmission alternatives in terms of establishing the degree of permissible gearing errors to meet a specified timing goal. This approach provides the tool for both evaluating the design prior to the build and test stage and also provides an illuminating tool for designing and confirmatory tests.

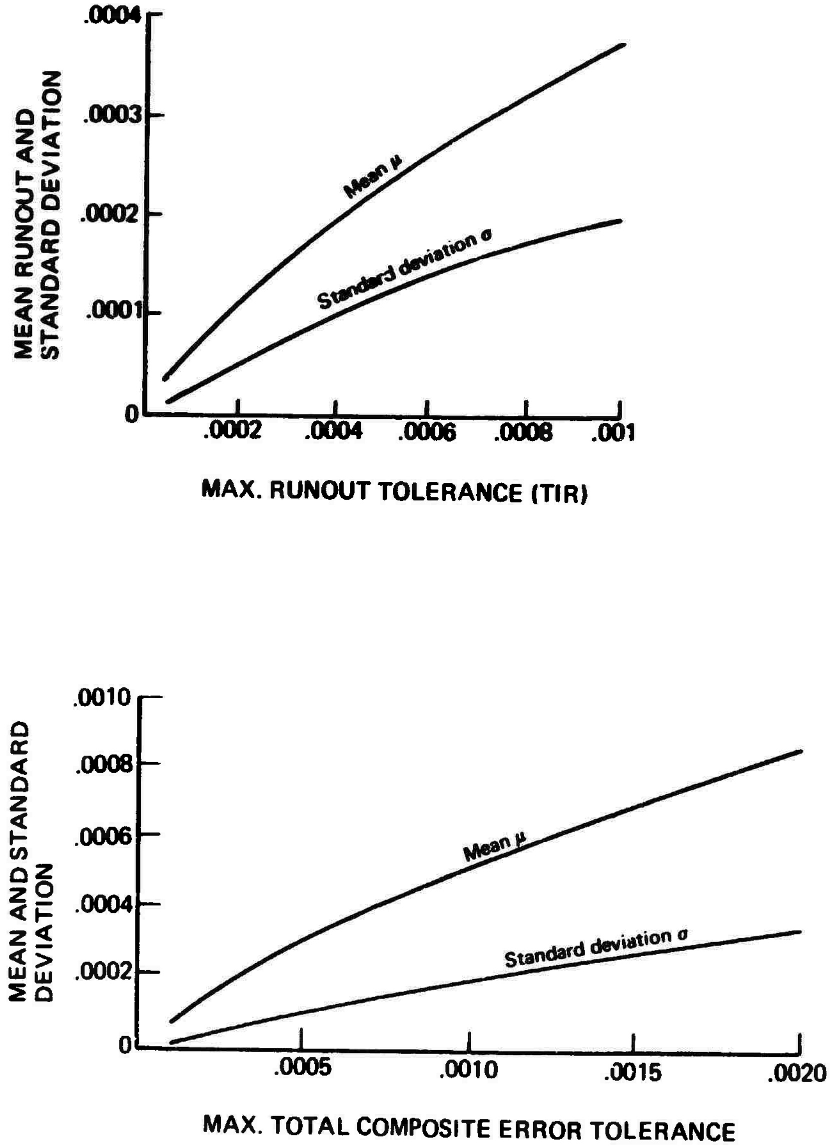


FIGURE 6 Statistical parameters for typical gear errors.

APPENDIX A TO CHAPTER V

PRECISION GEAR DRIVE

ANALYSIS

PRECISION GEAR DRIVE ANALYSIS

An analysis of a precision gear drive system was undertaken as a means for evaluating the impact of typical gear errors and bearings torque variations. It was anticipated that these errors would have a significant influence on the rotary motion of the system. Further, the system's dynamic performance was expected to be an indication of its sensitivity to aging.

The model for this case is an inertia load that is driven by an electric motor through a set of precision spur gears. An idealized schematic diagram of the system is shown in Figure 7. The system consists of four rigid elements, i.e., the motor rotor, the pinion, the gear, and the mirror (with initial load). These elements are connected by two flexible shafts.

A rotor torque, T_R, drives the system. This torque is dependent upon the rotor speed and is shown in Figure 8. A resisting torque due to windage acts on the mirror. This torque is considered to be a squared function of the inertia load's velocity.

In order to introduce dynamic errors into the system, the gear and pinion radii are introduced as functions of the gear eccentricity and tooth error. The gear eccencricity frequency is dependent upon the number of gear revolutions and the tooth error frequency is dependent upon the tooth contacts.

The torque equations are:

$$T_R = f(\dot{\theta}_R) \tag{1}$$

and

$$T_M = C_M \dot{\theta}_M^2 \, (\dot{\theta}_M / |\dot{\theta}_M|) \tag{2}$$

The radius of the pinion and gear are:

$$r_p = R_p + E_p \sin(\theta_p - \theta_{po}) + T_p \sin[N_p(\theta_p - \theta_{po})] \tag{3}$$

and

$$r_G = R_G + E_G \sin(\theta_G - \theta_{Go}) + T_p \sin N_G(\theta_G - \theta_{Go}). \tag{4}$$

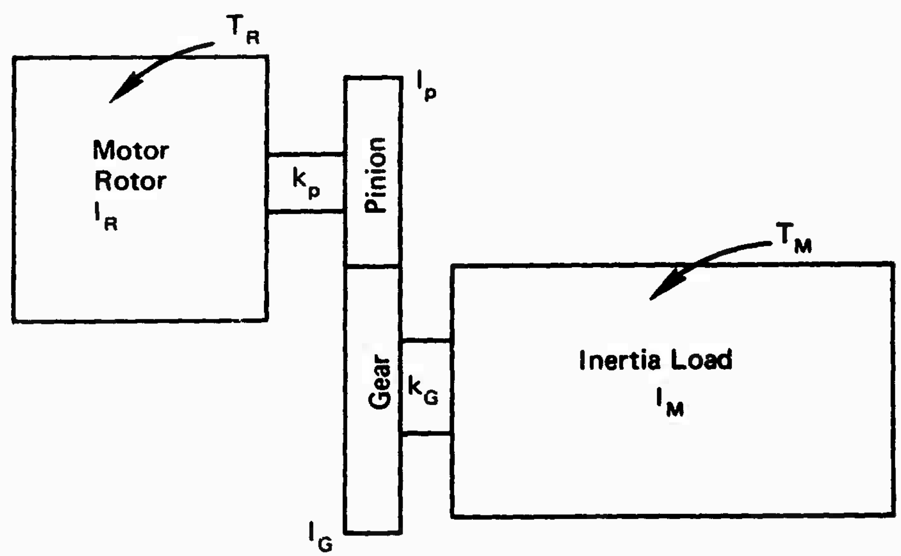
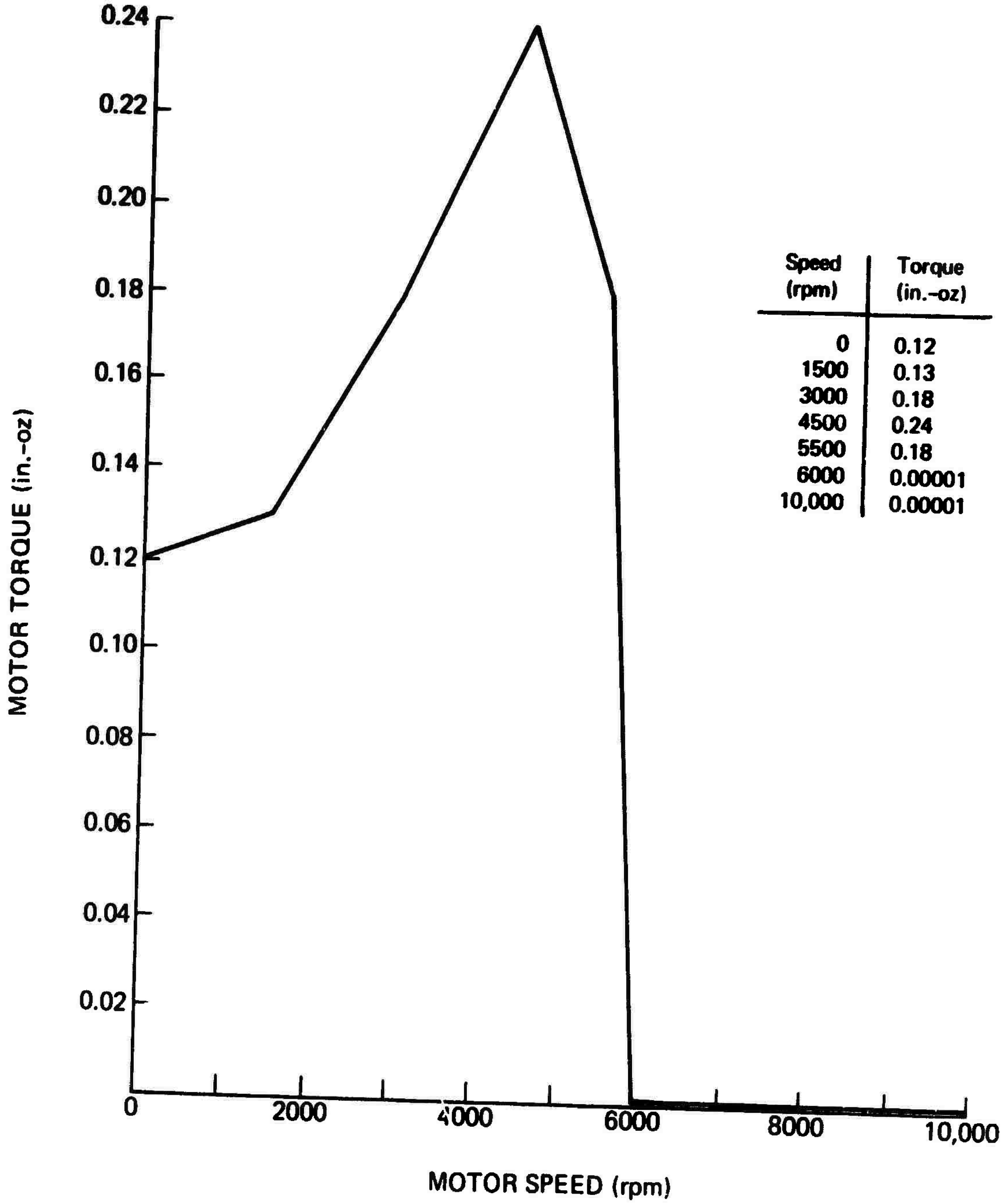


FIGURE 7 Mirror drive system.



Speed (rpm)	Torque (in.-oz)
0	0.12
1500	0.13
3000	0.18
4500	0.24
5500	0.18
6000	0.00001
10,000	0.00001

FIGURE 8 Typical induction motor torque characteristics.

The instantaneous velocity of the gear and pinion at the point of tooth contact is:

$$r_p\dot{\theta}_p = r_G\dot{\theta}_G. \tag{5}$$

Differentiating with respect to time,

$$\dot{r}_p\dot{\theta}_p + r_p\ddot{\theta}_p = \dot{r}_G\dot{\theta}_G + r_G\ddot{\theta}_G. \tag{6}$$

The radius equations are differentiated as:

$$\dot{r}_p = E_p\dot{\theta}_p \cos(\theta_p - \theta_{p\theta}) + T_pN_p\dot{\theta}_p \cos[N_p(\theta_p - \theta_{po})] \tag{7}$$

and

$$\dot{r}_G = E_G\dot{\theta}_G \cos(\theta_G - \theta_{Go}) + T_GN_G\dot{\theta}_G \cos[N_G(\theta_G - \theta_{Go})] \tag{8}$$

Let the rotor torque, T_R, be of the form:

$$T_R = T_{i-1} + (T_i - T_{i-1})(\dot{\theta}_R - \dot{\theta}_{i-1})/(\dot{\theta}_i - \dot{\theta}_{i-1}), \tag{9}$$

where T_i and $\dot{\theta}_i$ are the tabulated values of torque and angular velocity for the motor as shown in Figure 8.

The free-body diagrams for the drive system are shown in Figure 9. The equations of motion can now be written for the system. They are:

$$I_R\ddot{\theta}_R = T_R + K_p(\theta_p - \theta_R), \tag{10}$$

$$I_p\ddot{\theta}_p = -K_p(\theta_p - \theta_R) - Fr_p, \tag{11}$$

$$I_G\ddot{\theta}_G = K_G(\theta_M - \theta_G) + Fr_G, \tag{12}$$

and

$$I_M\ddot{\theta}_M = -K_G(\theta_M - \theta_G) - C_M\dot{\theta}_M^2(\dot{\theta}_M/|\dot{\theta}_M|). \tag{13}$$

These equations may be rewritten along with equation 6 as:

$$r_p\ddot{\theta}_p - r_G\ddot{\theta}_G = -\dot{r}_p\dot{\theta}_p + \dot{r}_G\dot{\theta}_G, \tag{14}$$

$$I_R\ddot{\theta}_R = T_R + K_p(\theta_p - \theta_R), \tag{15}$$

$$I_p\ddot{\theta}_p + r_pF = -K_p(\theta_p - \theta_R), \tag{16}$$

$$I_G\ddot{\theta}_G - r_GF = K_G(\theta_M - \theta_G), \tag{17}$$

and

$$I_M\ddot{\theta}_M = -K_G(\theta_M - \theta_G) - C_M\dot{\theta}_M^2(\dot{\theta}_M/|\dot{\theta}_M|). \tag{18}$$

Equations 15 and 18 can be solved directly for $\ddot{\theta}_R$ and $\ddot{\theta}_M$. The remaining three equations (14, 16, and 17) can be solved simultaneously for $\ddot{\theta}_p$, and $\ddot{\theta}_G$ and F, where F is the tooth contact force. The solutions are:

$$\ddot{\theta}_p = [-r_pI_G(-\dot{r}_p\dot{\theta}_p + \dot{r}_G\dot{\theta}_G) + r_G^2K_p(\theta_p - \theta_R)$$
$$-r_Gr_pK_G(\theta_M - \theta_G)]/(-r_p^2I_G - r_G^2I_p), \tag{19}$$

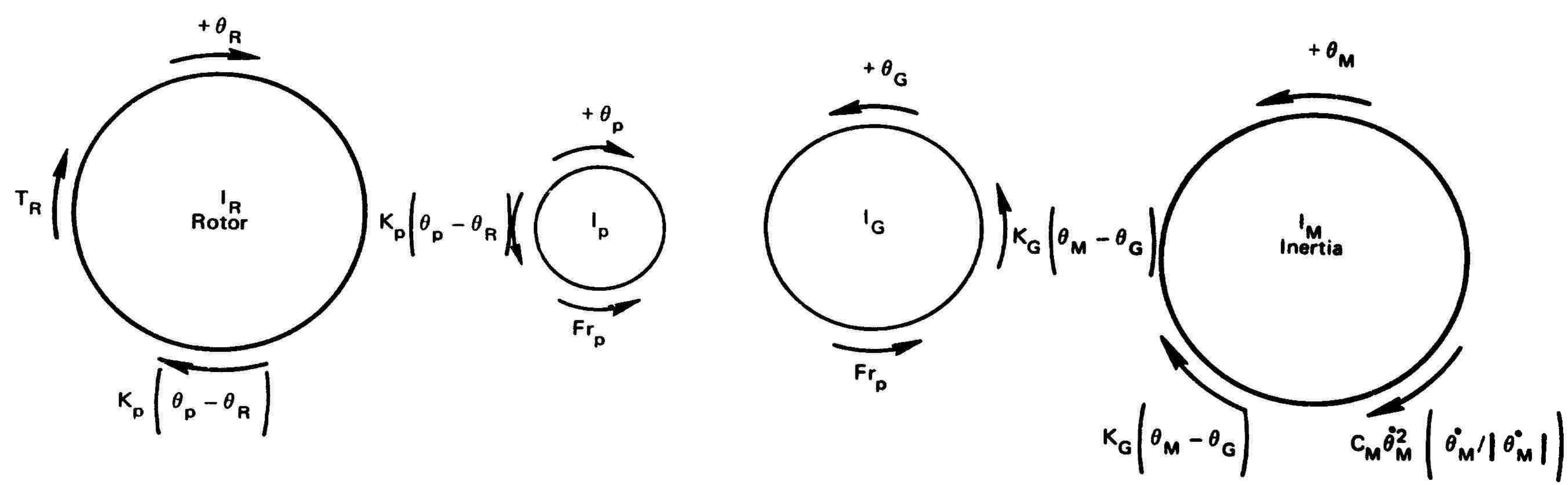


FIGURE 9 Free body diagrams.

$$\ddot{\theta}_G = [+r_G I_p(-\dot{r}_p\dot{\theta}_p + \dot{r}_G\dot{\theta}_G) + r_p r_G K_p(\theta_p - \theta_R) - r_p^2 K_G(\theta_M - \theta_G)]/(-r_p^2 I_G - r_G^2 I_p), \tag{20}$$

and

$$F = [I_G I_p(-\dot{r}_p\dot{\theta}_p + \dot{r}_G\dot{\theta}_G) + r_p I_G K_p(\theta_p - \theta_R) + r_G I_p K_G(\theta_M - \theta_G)]/(-r_p^2 I_G - r_G^2 I_p). \tag{21}$$

These equations were solved numerically. The early results, however, indicated the shaft stiffness values could be eliminated without affecting the results. By considering the shafts to be infinitely stiff, the following simplification was made:

$$\theta_r = \theta_p,$$
$$\dot{\theta}_r = \dot{\theta}_p,$$
$$\ddot{\theta}_r = \ddot{\theta}_p,$$
$$\theta_G = \theta_M,$$
$$\dot{\theta}_G = \dot{\theta}_M,$$

and

$$\ddot{\theta}_G = \ddot{\theta}_M.$$

With these substitutions, the motion equations become:

$$(I_p + I_R)\ddot{\theta}_p = -Fr_p + T_R \tag{22}$$

and

$$(I_G + I_M)\ddot{\theta}_G = Fr_G - C_M\dot{\theta}_G^2(\dot{\theta}_G/|\dot{\theta}_G|). \tag{23}$$

These equations can be solved simultaneously along with equation 6 to give:

$$\ddot{\theta}_P = [T_R r_G^2 - C_M r_P r_G \dot{\theta}_G^2(\dot{\theta}_G/|\dot{\theta}_G|) - (I_G + I_M) r_P \dot{r}_P \dot{\theta}_P + (I_G + I_M) r_p \dot{r}_G \dot{\theta}_G]/[(I_P + I_R) r_G^2 + (I_G + I_M) r_P^2], \tag{24}$$

$$\ddot{\theta}_G = (r_P\ddot{\theta}_P + \dot{r}_P\dot{\theta}_P - \dot{r}_G\dot{\theta}_G)/r_G, \tag{25}$$

and

$$F = [T_R - (I_P + I_R)\dot{\theta}_P]/r_P. \tag{26}$$

The bearings will be subjected to radical load variations due to vibratory motion of the base. In order to investigate the possible detrimental effect upon the main motion, a fluctuating torque was added on either side of the gear train. The torques are introduced as:

$$T_{BP} = (T_{CP} + T_{LP} V_P)\sin \pi\omega t$$

and

$$T_{BG} = (T_{CG} + T_{LG} V_G)\sin \pi\omega t.$$

Hence, the torques consist of a constant part and a velocity dependent part. The frequency of the torques is entered to the program as a vibration-induced frequency. The above equations are solved numerically. Nomenclature used in this analysis is presented below as are the parameters of a particular case. For this case, the impact of both dimensional errors and bearing run-out and torque variations were studied. It was determined that a cyclic transmission error of 0.011 degrees occurs every 100 milliseconds. The simulation described herein was used to evaluate the performance of gear train systems where maximum tolerable error was specified as 0.014 degrees every 90 degrees displacement. Figure 10 illustrates the computer-simulated transmission characteristic. It is seen that the margin for gear degradation or increased tolerance variation is quite small. Utilizing these techniques, a similar error analysis can be implemented to accurately predict the maximum permissible tolerance range for a given timing accuracy.

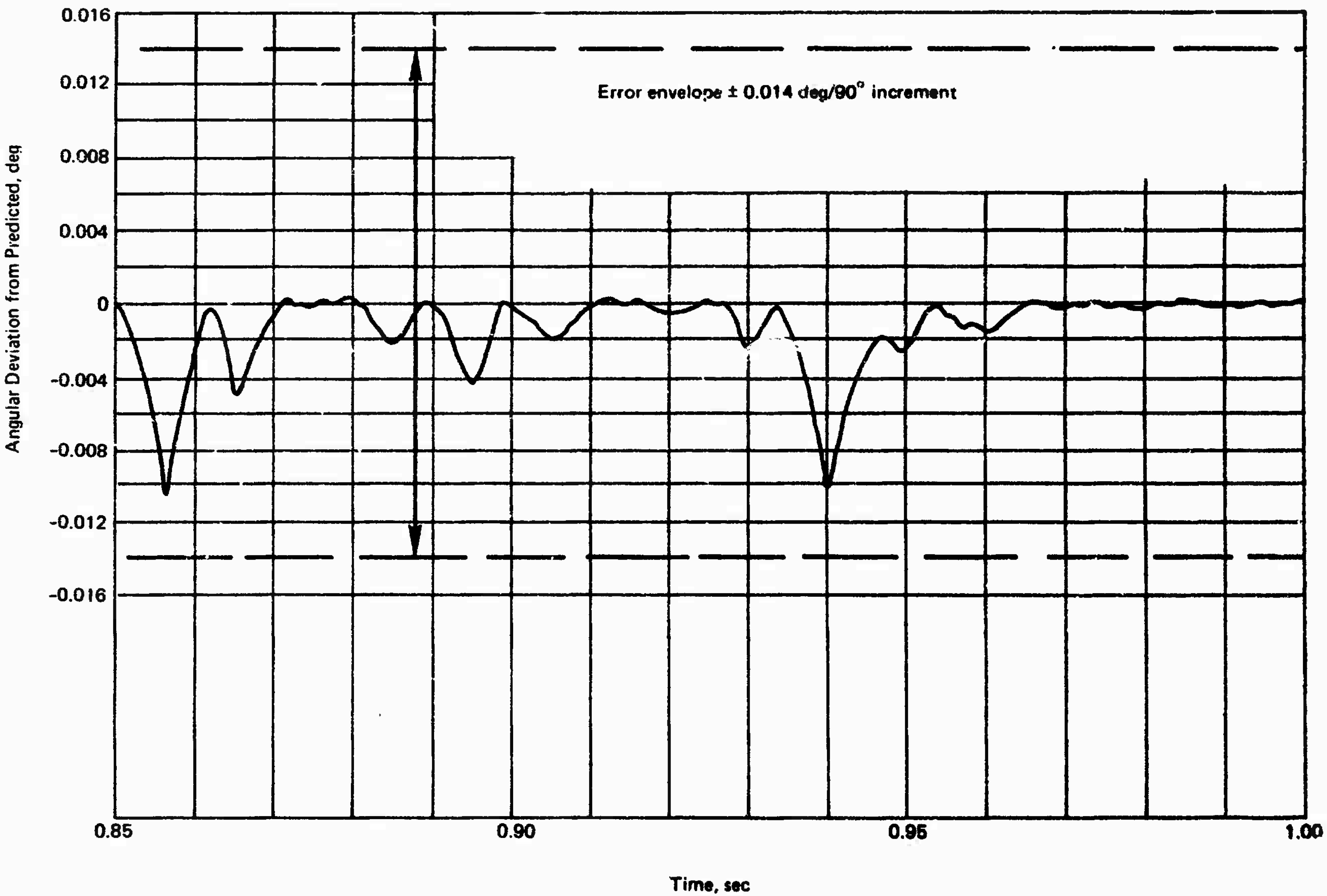


FIGURE 10 Angular output error.

NOMENCLATURE

I_R = 0.000656 in.-oz-sec², rotor moment of inertia

I_P = 0.000008 in.-oz-sec², pinion moment of inertia

I_G = 0.00368 in.-oz-sec², gear moment of inertia

I_M = 0.01968 in.-oz-sec², load moment of inertia

K_P = 592 in.-lz/rad, pinion-rotor shaft stiffness

K_G = 23,000 in.lz/rad, gear-mirror shaft

C_M = 0.4444 x 10^{-7} in.-oz/rpm², drag constant

r_P = 0.2083 in., pinion radius

r_G = 0.8333 in., gear radius

E_P = 0.125 x 10^{-3} in., pinion eccentricity amplitude

E_G = 0.125 x 10^{-3} in., gear eccentricity amplitude

T_P = 0.100 x 10^{-3} in., pinion tooth error amplitude

T_G = 0.100 x 10^{-3} in., gear tooth error amplitude

N_P = 30, pinion teeth

N_G = 120, gear teeth

$$\left.\begin{array}{l} T_{CP} = 0.01 \\ T_{LP} = 0.00000167 \\ T_{CG} = 0.01 \\ T_{LG} = 0.00000167 \end{array}\right\} \text{bearing torque constants}$$

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VI. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations result from the Committee's consideration of alternate methods for production of fuze pinions. New processes, new materials, and new designs are included. The feasibility of each alternative was considered by the Committee in terms of both technical and economic factors using data that were available and the experience of the Committee members, Liaison Representatives, and Consultants. Major attention was given to materials and production methods; no detailed consideration was given the redesign of fuzes.

1. Four production methods, for which a civilian technology base exists, show promise as alternates to the current practice of manufacture of fuze pinions by machining:
   a. Zinc die casting
   b. Plastic molding
   c. Powder metallurgy
   d. Chemical-etch/diffusion-bond processing

   All four methods would require modest redesign of the pinion and, possibly, the fuze in order to obtain maximum utility of the particular method and to offset possible processing and material shortcomings. All four methods currently are growing as manufacturing techniques in this country and should assure a base for pinion production in the future. All four methods appear to be capable of producing pinions at costs equivalent to (or possibly below) current pinion production costs. All four methods are capable of very high rates of production, using relatively unskilled personnel.

2. Zinc die casting is recommended specifically as a bonding technique for joining the blanked brass gear to a machined steel shaft, with the joint region being in the form of the pinion. This method allows for a high-strength shaft, strong and wear-resistant pivots, and a conventional gear in the pinion/gear assembly. The relatively low strength of zinc die casting

alloys may be a problem but could be offset partially by casting a flange on the pinion at the end where it is joined to the gear.

3. Plastic molding by injection is recommended as a method for producing either the entire pinion/gear assembly from a polymeric material or a pinion and gear on a machined steel shaft to provide increased strength and pivot strength. Both static strength and creep strength may be limitations with these materials. However, new developments in polymeric materials and redesign of the pinion/gear assembly could offset these difficulties.

4. Powder metallurgy is recommended as an alternative for producing pinions and, possibly, also gears. A standard press-and-sinter process could be used, followed by a subsequent coining operation to obtain necessary tolerances and surface finishes. The pinion and gear would be assembled on a pre-machined steel shaft.

5. Chemical etching/diffusion bonding is recommended as a means for producing laminated pinions by photoetching thin sheets to form pinion profiles and subsequently diffusion bonding these to form the pinion. A steel shaft would be bonded into the laminate stack to provide the pivots. The gear could be either blanked from a brass sheet or made by this new method and then bonded into the assembly as well.

6. Some development effort would be needed to establish technical feasibility for each of these four methods. Economic factors could be established in detail at this time. However, it is anticipated that these programs would be modest in scope and expense since they would build on an existing technology base.

7. It is recommended that a study be undertaken to determine the effects of gear and pinion dimensional tolerances on the overall performance of the fuze. It is possible that present tolerances are too severe, resulting in high production costs, difficulties in developing new processes, and limited numbers of domestic fuze pinion producers. Furthermore, it may be possible to combine looser tolerance gears in a fuze in such a way that the present fuze timing specifications are still achieved.

8. It is recommended that a study be undertaken to determine specifically the material properties (especially mechanical and corrosion) that are necessary in fuze pinions and gears. Such information will be of value in allowing for the substitution of new materials into fuzes in the future.

9. It is recommended that the following suggestions be given consideration in regard to the planning of fuze utilization, the selection of fuze materials, and the design of fuzes:

   a. The specifications for fuzes for stockpiling and fuzes for immediate use should be considered separately since the lifetimes expected and the materials required can vary widely. Lower cost, lower quality materials (and processes) could be acceptable for fuzes produced for immediate use.

   b. The use of a wider variety of materials in fuzes should be considered as an alternate to the limited number presently used. The loading on pinions, for example, becomes progressively lower along the gear train in a fuze. A mix of materials in the gear train, each material being selected according to the load it would experience, could greatly reduce the demand for pinions manufactured by the present machining process.

c. The overall design of the fuze should be reconsidered in order to eliminate spring loading of the gear train until the moment of use. This would allow for a wider variety of materials (and processes) to be considered for fuze pinions and gears (e.g., low creep strength materials).